EXPERIMENTAL INVESTIGATION OF NOZZLE/PLUME AERODYNAMICS AT HYPERSONIC SPEEDS

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Wedge model test data was reduced and written up. Theoretical calculations were made and were found to be in reasonably good agreement with the experimental data. The results were presented at the 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference at Nashville, TN. The new test section was calibrated at 6000 psi driver pressure and equivalent flight Mach numbers of 12, 14 and 16. A rake with pitot pressure, static pressure and stagnation heat transfer heads, along with nozzle wall static pressure measurements and facility measurements, was used to calibrate the tunnel. A contamination-free test time of 3-5 ms was found and the full impact pressure core flow diameter was found to be ~70 cm (70% of the nozzle exit diameter). The combustor model has been installed in the new test section and testing is underway. The hydrogen fuel system for the combustor model has been designed, safety approvals have been obtained, all parts are in hand and assembly and pressure checking are about 90% complete. Final checkouts and calibrations remain to be done before the first tests are performed (estimated to be made in the first week of December).

Preliminary studies were made on the construction of

I. SUMMARY

The work performed by D. W. Bogdanoff and J.-L. Cambier over the time period 1 February 1992 to 31 October 1992 involved the following. Work continued on improvements in the operating techniques of the 16 Inch Shock Tunnel. The voltage on the capacitor bank used to ignite the driver gas was reduced from 14 to 11.3 kV, resulting in smoother driven gas burns. Gas loading manifolds with improved injection hole profiles, more resistant to burn out, were introduced. Improved manifold hold downs were also introduced. The preliminary design for a mix on-the-fly system for loading the driver gas was further developed. Studies were made on the reduction of contamination by ablated wall material, increase of test time through the use of a buffer gas and/or an annular barrier at the nozzle entrance, a number of facility mechanical improvements, a throat valve to eliminate model damage by debris, the use a nickel diaphragms to reduce petal loss, a converging driven tube to increase the reservoir pressure and enthalpy, operation of the tunnel in non-reflected shock or expansion tube mode and the construction of a larger test section.

a 3" shock tunnel to support the 16 Inch Shock Tunnel. The tunnel would be used for the development and calibration of diagnostic techniques and for the development of new tunnel operation techniques. The work on diagnostic techniques would include development of thermal and mechanical protection for pressure transdcuers, development of skin friction gauges, calibration of all types of surface gauges and development of a number of optical techniques, including fiber optic and diode laser techniques, resonant holography and PLIF. A number of components which could be used to construct this tunnel have been located.

Theoretical (CFD) work includes steady and unsteady modelling of the flows in the 16 Inch Shock Tunnel. The steady flow work includes modelling the facility nozzle flow, flow over the wedge model and the shock structure at the combustor model inlet. For the wedge model, reasonably good agreement has been found between the CFD results and experimental data. The unsteady flow work included modelling the unsteady flow in the driver and driven tubes, the rupture of the primary diaphragm and shock reflection, transmission and focussing at the nozzle entrance. In addition, the startup of flow in the EAST facility was modelled. CFD results from the unsteady modelling of the driver and driven tube were found to be in good agreement with experimental pressure histories.

A pulsed detonation wave engine operating in conjunction with a steady flow scramjet engine was modelled. Such an engine configuration has the potential to provide additional thrust and improved mixing and combustion compared to the usual steady flow scramjet combustors. The Ames DCAF facility was also modelled. Multiple temperatures and the principle of detailed balance were used in the latter models.

High temperature shock layers, both equilibrium and non-equilibrium, were modelled. The flow over the Rosetta probe vehicle is at relatively high pressure and was modelled as an equilibrium flow. Heat flux rates at the body surface were calculated. Non-equilibrium calculations were made for argon plasmas. A full collisional-radiative model was used. These results will be used in conjunction with Ames' high-enthalpy shock tubes and arcjets.

Modelling was begun of reactive shock waves and detonation waves in high density gases and dense media. A Godunov equilibrium code is also being developed for use in high density gases and dense media. Both of these models will be useful in media where the equation of state is very far from that of an ideal gas.

II. DETAILED DISCUSSION, EXPERIMENTAL WORK

A. Improvement in operation of facility

In this contract period several techniques for improvement of the operation of the Ames 16 Inch Shock Tunnel were implemented and preliminary studies were made on a number of other techniques. Reduction of the voltage of the capacitor bank used to heat the driver ignition wires has already been shown to improve the quality of (i.e, smooth out) the driver burn. In earlier work, this voltage was reduced from 18.5 to 14 kV. In the present contract period, the voltage was further reduced from 14.0 to 11.3 kV, resulting in further improvement of the driver burn. This voltage reduction was accomplished without reducing the maximum wire temperature by using finer wires. Still finer wires were purchased and additional capacitors for the capacitor bank were located.

Using the latter wires and the additional capacitors would allow the bank voltage to be still further reduced to 8-9 kV in the future.

A new design of the injection holes in the driver gas loading manifold was implemented. This design uses electric discharge machined holes which have a larger length-to-diameter ratio and hence improved resistance to burn-out. New hold-downs for the manifold were also implemented. These hold-downs allow for freer motion of the manifold and should be less subject to being ripped off the driver tube wall in operation.

Further studies were made on the driver gas mix-on-the-fly system. Such a system would mix He/O_2 premixed gas and H_2 before loading them into the driver. The better mixing obtained with this system should produce smoother driver burns and lessen the danger of detonations, would eliminate the driver manifold and the associated expense and labor and would eliminate the 2 hour wait after driver gas loading (for mixing) before ignition. A near final configuration for this system was made and vendors were located for components and price and delivery information obtained.

A number of other techniques for facility improvement were studied. These include short term, intermediate term and long term items. The short term items were:

- Reduction of contamination from wall ablation by the use of molybdenum, columbium or tantalum for nozzle throats and the driven tube end wall
- Modification of the driver mounting to allow axial translation of the driver to speed up the tunnel turn around

The intermediate term items were:

- Use of a buffer gas and/or an annular barrier at the nozzle entrance to increase the driver-gas-free test time
- Operation of the tunnel in a very high enthalpy equilibium interface mode
- Improvement of the diaphragm clamping section to allow better control of the diaphragm petals and to minimize or eliminate petal loss
- Improvement of the annular piston used to clamp the main diaphragm to reduce the piston stresses
- Use of a cylinder throat valve downstream of the

nozzle throat to eliminate model damage due to debris

- Use of nickel diaphragms to reduce or eliminate diaphragm petal loss

The long term items were:

- Use of converging driven tube to increase the driven tube reservior pressure and enthalpy (see Sec. III and Ref. 1)
- Operation of the tunnel in the non-reflected shock mode
- Operation of the tunnel in the expansion tube mode
- Operation of the tunnel with a much enlarged test section allowing the test of a 1/3 scale model of a complete scramjet engine

B. Wedge model

The chord and span of the wedge model are 38 cm and 46 cm, respectively. The model has five 30^o 0.305 cm diameter hydrogen injection ports arranged in a spanwise row at about mid chord. The model was operated at an angle of attack of 11^o . The model instrumentation includes 12 static pressure transducers (Kulites) and 14 heat transfer gauges on the model surface. Two pitot probes are located at the model leading edge and a seven head pitot rake is located at the trailing edge. Laser holographic interferograms can be taken in the spanwise direction. The hydrogen fuel system can inject room temperature hydrogen at plenum pressures up to 27 atm. Two pressure transducers measure the hydrogen plenum pressure and the mass flow is measured using a venturi.

Three types of tests were run. Tare runs used air as the driven tube gas with no hydrogen injection. Mixing runs used nitrogen driven tube gas with hydrogen injection. Finally, combustion runs used air driven tube gas with hydrogen injection. Six runs were made at 272 atm driver pressure and Mach 14 enthalpy, comprising one tare run, two mixing runs and three combustion runs. One of the three combustion runs was made at twice the hydrogen mass flow rate of the other two runs. (We will refer to this run as the "high-q" run.) One 272 atm driver pressure run was made at Mach 16+ enthalpy. Two runs, a mixing and a combustion run, were made at 408 atm driver pressure and Mach 16 enthalpy.

The discussion below deals with 272 atm driver pressure data only. For the tare runs the static pressures were nearly identical over the whole wedge surface, as expected. With hydrogen injection, pressure increases due to the hydrogen plume shocks could be seen. These pressure increases were larger for the high-q run. The aft pitot rake showed the wedge shock location and the reduction in dynamic pressure due to the hydrogen injection plume. The reduced dynamic pressure area was larger for the high-q run. The wedge shock moved further away from the wedge surface with injection, presumably since the plume shock merged with the wedge shock and strengthened it.

The heat flux data for the tare run showed greatly increased heat flux aft of the injection holes, presumably as result of the holes tripping the boundary layer. For the gauges just aft of the injectors, no effect could be seen midway between the injectors, However, gauges midway between the injectors and just upstream of the trailing edge also showed this increse, indicating that the tripped region was spreading laterally. With injection, gauges on the injector centerlines showed a reduction of heat transfer downstream of the injectors, likely a result of hydrogen film cooling. With injection, for the gauges midway between the injectors, the heat flux increased downstream of the injectors, likely a result of plume shock compression.

The laser holographic interferograms showed the wedge shock, the plumes of hydrogen up to the pitot rake and the plume shock merging with the wedge shock near the trailing edge of the model. CFD calculations of the flow were made and surface static pressures, heat fluxes, shadowgraphs and interferograms were computed and compared with the experimental results obtained. Overall, reasonable agreement between theory and experiment was obtained. These results were presented as AIAA Paper 92-3288 at the 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference in Nashville, TN, July 6-8, 1992 (Ref. 2).

C. Calibration of new test section

The new test section was calibrated at driver after-burn pressures of 6000 psi and effective flight Mach numbers of 12, 14 and 16. A 35-head probe with a one inch probe spacing was used. The probe was located roughly at the nozzle exit and could be translated in the vertical and fore-and-aft directions and rotated. Heads on the probe could measure total pressure, static pressure and stagnation point heat transfer. Static pressures were also measured at several points along the nozzle, including at the nozzle exit. Pitot profiles were obtained at an effective nozzle area ratio of 170. Typically, the pitot pressure of the core flow is $\sim$4.0 atm and full pitot pressure extends over $\sim$70 cm or 70% of the nozzle exit diameter. The driver-gas-free test time can be estimated from from measurements of rake pitot pressure, rake stagnation point heat transfer, nozzle wall static pressure, test section total radiation and laser based free stream temperature data. The test times are estimated to be 3-5 ms for Mach 12 and 14 conditions and 2-3 ms for Mach 16 conditions. Additional measurements of test time may be made in the future using spectoscopic measurements of driver gas He arrival or direct photographic measurements of changes in the shock angle on a wedge upon arrival of driver gas He.

CFD computations were made of the unsteady flow in the driver and driven tubes and of the nozzle flow. Computed pressure histories in the driver and driven tubes were compared with experimental data and excellent agreement was found. These results were presented, in part, as AIAA Paper 92-3810 at the 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference in Nashville, TN, July 6-8, 1992 (Ref. 3).

D. Combustor model

The combustor model is installed and the test program is underway. To date, only tare runs (without fuel flow) have been made. Runs with fuel injection will begin about 12/1/92. Tests have been made at 6000 psi driver pressure and at Mach 12, 14 and 16 enthalpies. Data obtained from the model includes static and total pressures, surface heat flux and laser holographic interferograms.

E. Hydrogen fuel system for combustor model

The hydrogen fuel system is almost completed at this time and will be operational shortly. Work done over the contract period includes the following. Final changes were implemented for the mounting of the hydrogen storage vessels and the feed lines from the vessels to the model. The final design reviews were made and safety approvals obtained. Stress analyses and temperature change calculations were made and given to Ames safety personnel. All commercial off-the-shelf items were procured and are in hand. The hydrogen storage spheres (with full documentation) were received from March Metalfab. The specially designed parts were machined in the Ames shop and are in hand. Most of the plumbing is completed, in place and labelled as required. The electrical control system was designed, assembled and is in place. Test, calibration and operating procedures have been written. The drawings of the system have been assembled and placed on file in the Ames archive system.

The final hydrotests, gas leak tests, assembly, all-up operational tests with helium and injector calibrations with air will be done in late November, 1992. Operation with hydrogen fuel is expected about 12/1/92.

F. Three inch calibration/development tunnel

It is intended to construct a three inch shock tunnel in 1993 in order to support the work of the 16-Inch Shock Tunnel. This tunnel will be used to develop and calibrate diagnostic techniques and to develop operational techniques which may be useful on the large tunnel. A number of components which will be used in the three inch tunnel have been located and the basic tunnel configurations have been developed.

The development and calibration of diagnostics will include surface, probe and non-intrusive optical measurements. The work on surface and probe measurements may include studies of pressure transducer thermal protection and shielding geometries, skin friction gauge development and calibration of heat transfer gauges as well as the other types of gauges. The work on optical techniques will include studies of holographic interferometry, dye laser absorption techniques (for OH and NO), fiber optics and diode laser techniques, resonant holography (RHIS) and PLIF.

The tunnel operational techniques which may be investigated include use of a buffer and/or an annular barrier at the nozzle entrance to increase the driver gas free test time, a converging driven tube to increase the driven tube reservoir pressure and enthalpy, the use of nickel diaphragms to reduce or eliminate the loss of diaphragm petals, the use of molybdenum, tantalum or columbium for nozzle throats and driven tube end walls to reduce wall ablation flow contamination, measurements of the arrival time of driven gas helium using spark spectroscopy or direct photography of the change of the shock angle on a wedge and the use of a cylinder throat valve to protect the model from damage by debris.

III. DETAILED DISCUSSION, THEORETICAL WORK

A. General

The theoretical work performed during 1992 encompasses several topics. The primary focus of our investigation concerned the shock tunnel, and particularly the computations deemed necessary for the NASP GWP 53 activity. However, several other related topics were also investigated, with some having direct relevance to the shock tunnel, while others attempt to supplement the computational capability in simulating flows in other facilities at Ames. Other topics are concerned with the evaluation of new concepts in hypersonic propulsion, or the evaluation of nonequilibrium effects in shock layers at high velocities. The work performed is described below, according to the tasks.

B. NASP GWP 53 task

This work was performed by D. Prabhu, S. Tokarcik and Dr. J-L. Cambier. The 1D/2D Reacting Navier-Stokes

"MOZART", developed by Dr. Cambier, was used for several calculations:

1. Calculation of the steady nozzle flow for conditions given by the experimental investigators (8000 lbs, Mach 14).
2. Calculations of the steady nozzle flows using the quasi-1D code for several test conditions. Correlation with the 2D axisymmetric solution obtained for Mach 14.
3. Calculations of the shock structure in the combustor inlet. Several calculations were performed, by varying several parameters: turbulent vs. laminar boundary layers and Mach 12, 14 and 16 conditions. A grid sensitivity was also performed. The calculations showed the extent of separation in front of the shock-BL interaction for off design cases, and verified the shock cancellation for the on-design (Mach 14) condition.
4. Calculations of the flow on a wedge. The Mozart-2D code was used again, and the calculations were performed for laminar and turbulent conditions, and included a grid sensitivity analysis. The solution was found to be in excellent agreement with the computational results

performed at NASA-Langley, using the SPARK-3D code, and in good agreement with the experimental data.

5. The same flow was computed using the 3D version of the MOZART code, to examine the 3-dimensional effects of the shock curvature on the density field. The solution was used to compute a theoretical interference fringe pattern, which was compared with the experimental one. The agreement was considerably better than with a 2D solution.

6. New 2D axi-symmetric calculations of the nozzle flow were initiated after the correct experimental conditions were finally obtained from the experimental investigators. The work on the mass capture in the inlet (3D) was also initiated.

C. Shock Tunnel Unsteady Flow

This work was performed by S. Tokarcik and Dr. J-L Cambier. The MOZART/2D code was used to simulate several important unsteady processes, in order to better understand the characteristics of the shock tunnel operation.

1. The shock reflection and transmission process at

the end of the driven tube and converging section of the nozzle was thoroughly examined. It was found that the shock convergence mechanism on the axis creates severe numerical difficulties, which were not properly appreciated by other investigators. We found that some simple remedies could be found to alleviate the formation of unphysical shock structures near the axis. The calculations were repeated for several geometrical configurations, to also examine the effect of throat diameter and wall tapering on the vortex formed behind the reflected shock.

2. The primary diaphragm rupture process was also investigated in a preliminary study. The code was modified to allow for unsteady boundary conditions: the diaphragm rupture was modeled by a step-wise increase of the number of computational cells put into contact with the high pressure driver gas. The code was also enhanced to allow for subscaled grids overlayed on top of coarse background grids, and which could slide along a given direction, at a

given rate (automatically controlled). This preliminary attempt at solving a very difficult problem showed some deficiencies in the model of diaphragm rupture, but nevertheless paved the way for future, more accurate computations. The results also showed that the primary shock becomes planar very rapidly, while the contact discontinuity does not. This may have a very important impact on the flow quality and test time in the 16" shock tunnel.

3. The startup flow in the nozzle of the EAST facility was also investigated. This calculation was performed with great detail, using a subscaled overlaid grid to better capture the flow features during the transient. This allowed us to perfect the technique of subscaled overlaid grids. The calculations were performed for both inviscid and viscous cases, showing the importance of viscous terms for these conditions. These calculations were also initiated as a validating case: the nozzle is planar, and therefore any complication due to the treatment of shocks

collapsing on the axis is removed. Additionally, there is some experimental data available for this nozzle, and the comparison will be studied in the near future.

4. The propagation of the shock down the driven tube and reflection/transmission process was also computed in quasi-1D for varying geometries of the driven tube. This series of calculations were performed for investigator D. W. Bogdanoff, to investigate the concept of tapering the driven tube, in order to obtain higher reservoir pressures. The effect of shock focusing on the flow quality (i.e. steady conditions at reservoir) was looked for. Several parametric studies were performed, after consultation with D. W. Bogdanoff. The results were used to demonstrate the concept validity to NASA Headquaters, and will be compiled and presented as a paper at the upcoming Aerospace Sciences meeting in Reno, January 1993 (Ref. 1).

D. Pulsed Detonation Wave Engine

A DDF proposal was written and submitted by Dr. Cambier last year, and funded at the beginning of 1992. The proposed work concerned the design and study of a technique for using a Pulsed Detonation Engine in conjunction with a conventional scramjet combustor, for generating additional thrust and also stimulating the mixing and combustion process in the scramjet. The initial thrust of this work is to demonstrate the effectiveness of the detonation waves in stimulating the mixing and combustion in the supersonic mixing layers, during the interaction process. Several configurations will be studied by CFD, using the MOZART/2D code. The calculations are well under way. This preliminary work was also demonstrated to several investigators from General Dynamics during a recent visit at Ames. They showed considerable interest in both the numerical tools and the proposed engine concepts.

E. DCAF Flow Simulation

Another DDF proposal was written and submitted by Dr. Cambier and H. Adelman last year, and was also funded. The work on this DDF was delayed, due to more immediate commitments with the NASP GWP 53 activity. The proposed work is to devise experimental techniques and uses for the high pressure arc-jets at Ames, for propulsion testing. The work includes the generation of appropriate computational tools for simulating all aspects of the flow in this type of facility. The work recently performed consisted of a generalization of the MOZART-2D code to multiple temperatures. From our past experience in thermal nonequilibrium flow simulations and algorithm and model development, we devised a new and more complete thermo-chemical model. In this unique model, the coupling between chemical processes and internal energy modes is more detailed and fully consistent. Notably, the model accounts for the change in internal temperatures due to dissociation and recombinations. Contrary to other models, we have statistically computed and tabulated the average energies removed by dissociation. The average energy replaced during recombination is obtained by application of the principle of detailed balance. This model has the property of restoring thermal equilibrium as well as chemical equilibrium, without relying on other relaxation processes (such as Landau-Teller). This important physical property gives us a greater confidence in the accuracy of the model. The model also distinguishes between electronic (excited states and free electrons combined) and vibrational temperatures. This distinction is important in flows where the degree of ionization falls rapidly. The code has been applied to the planar nozzle used presently in the DCAF for a combustion experiment: the results shows a small degree of thermal nonequilibrium: this should alleviate the concern of the investigators at NASA-Langley, who communicated to us their interest in this problem.

F. High Temperature Shock Layer Simulation

The flow around the ROSETTA probe vehicle was computed, at the request of M. Tauber, for the conditions of peak heating at re-entry. The conditions are at sufficiently high pressure that chemical equilibrium could be assumed. Nevertheless, a solution with chemical kinetics was desired, to verify this assumption and convince the European partners. The calculations also required the evaluation of the convective heating at the body surface, for catalytic conditions. The MOZART-2D code was enhanced to allow for catalytic boundary conditions, and the thermal properties of the gas species were recomputed more accurately and for a higher temperature range. The calculations were performed for both non-catalytic and catalytic walls. A grid sensitivity study was also performed, in order to accurately estimate the temperature and concentration gradients near the wall. The results were used by M. Tauber for a report to JPL center, and will also be presented separately at the next Thermophysics Conference in 1993.

G. High Temperature Shock Layer Simulation

A series of codes for nonequilibrium plasma simulations, code-named "MAHLER", were initially developed by Dr. Cambier during the past two years, and have been consistently improved. The most advanced version uses a single-fluid description, and has been enhanced to a full Collisional-Radiative model. The thermo-chemical model for molecular species has also been developed, is presently being implemented, and validating calculations will soon be under way. The algorithms are also being improved to use of a more stable, implicit method which strongly couples all relaxation processes. Calculations concerning an argon plasma are still being pursued, with detailed parametric studies. An exhaustive report on the numerical techniques, computational results and physical interpretations, is planned in the near future, and the data are presently being compiled. This report will be in addition to the research papers already presented at the past Plasma Dynamics Conferences. This unique tool allows for very detailed investigations of the flow in high enthalpy shock tubes or arc-jets, and helps us discover some important physical phenomena.

G. More advanced developments

A more recent work concerned the development of an advanced code for the simulation of reactive shock propagation in condensed matter or high pressure gas, with non-ideal equation of state (EOS). A preliminary code was written which still uses the TVD technique of decomposition in terms of characteristic fields, but with a general EOS, tabulated. Preliminary tests of the new algorithm were conducted satisfactorily. Future work will include a validation of the technique and use of the Sesame library of EOS, recently acquired by co-investigator D. W. Bogdanoff. This code will be used to simulate shock tunnel operation for very high reservoir pressures, and for simulaion of detonation in solid explosives.

H. One-dimensional Godunov CFD code

A one-dimensional Godunov CFD code is under development. This code will have the ability to use a non-ideal gas equation of state and will include the modelling of frictional and heat transfer effects to the tube and tunnel walls. It will be used for further studies of the use of a converging driven tube to increase the reservoir pressure and enthalpy and studies of operation of the shock tunnel in non-reflected shock and expansion tube modes. The converging driven tube technique applied to non-reflected tunnel operation will also be studied.

I. Publications

References 4-8 are publications resulting from the theoretical work which have been or will be presented at conferences.

REFERENCES

1. Bogdanoff, D. W. and Cambier, J.-L., "Increase of Stagnation Pressure and Enthalpy," AIAA Paper 93-0350, to be presented at the 31st Aerospace Sciences Meeting, Reno, NV, January 11-14, 1993.

2. Loomis, M. P., Zambrana, H. A., Bogdanoff, D. W., Tam, T. C., Cavolowsky, J. A., Newfield, M. E. and Bittner, R. D., ''30 Degree Injectors at Hypervelocity Conditions," AIAA Paper 92-3288, presented at the 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Nashville, TN, July 6-8, 1992.

3. Cavolowsky, J. A., Loomis, M. P., Bogdanoff, D. W., Zambrana, H. A., Newfield, M. E. and Tam, T. C., ''Flow Characterization in the NASA Ames 16-Inch Shock Tunnel," AIAA Paper 92-3810, presented at the 28th AIAA/SAE/ASME /ASEE Joint Propulsion Conference, Nashville, TN, July 6-8, 1992.

4. Cambier, J.-L. and Prabhu, D., "Numerical Simulations of Nonequilibrium Shock Layers with a Highly Efficient Implicit Scheme", presented at the 23rd AIAA Plasma Dynamics and Lasers Conference, Nashville, TN, July 1992.

5. Cambier, J.-L., Tokarcik, S. and Prabhu, D., "Numerical Simulation of Unsteady Flow in a Hypersonic Shock Tunnel Facility", presented at the 17th AIAA Ground Testing Conference, Nashville, TN,

July, 1992.

6. Cambier, J.-L. and Tauber, M., "Computations of Nonequilibrium Shock Layers for the Comet Sample Return Vehicle", to be presented at AIAA 28th Thermophysics Conference, Orlando, FL, July 6-8, 1993.

7. Cambier, J.-L., Adelman, H. G. and Menees, G. P., "Numerical Simulation of a Pulsed Detonation Wave Augmentor Device", to be presented at 29th AIAA Joint Propulsion Conference, Monterey, CA, June 28-July 1, 1993.

8. Cambier, J.-L. and Moreau, S, "Numerical Simulation of a Molecular Plasma in Collisional-Radiative Nonequilibrium", to be presented at the 24th AIAA Plasma Dynamics Conference, Orlando, FL, July 6-9, 1993.

References (1) through (5) are attached as Appendix to this report; references (6) through (8) are in preparation and will become part of a future progress report.